CONFRONTING CLIMATE CHANGE

PREVENTING, PREPARING AND ADAPTING FOR A SECURE FUTURE

A compendium of essays for the
Allianz Climate Risk Research Award 2021

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Climate Risk
Research Award

Allianz

ABOUT THE COMPENDIUM

The Allianz Climate Risk Research Award supports young scientists whose research improves our understanding of climate change-related risks. The 2021 Edition supports researchers whose work focuses on:

- Reducing the risk of extreme weather events that are intensified by climate change
- Fostering resilience by applying technological solutions

The compendium is a compilation of selected essays from participants of the 2021 Edition. This compendium is issued online only and is published exclusively for didactic purposes.

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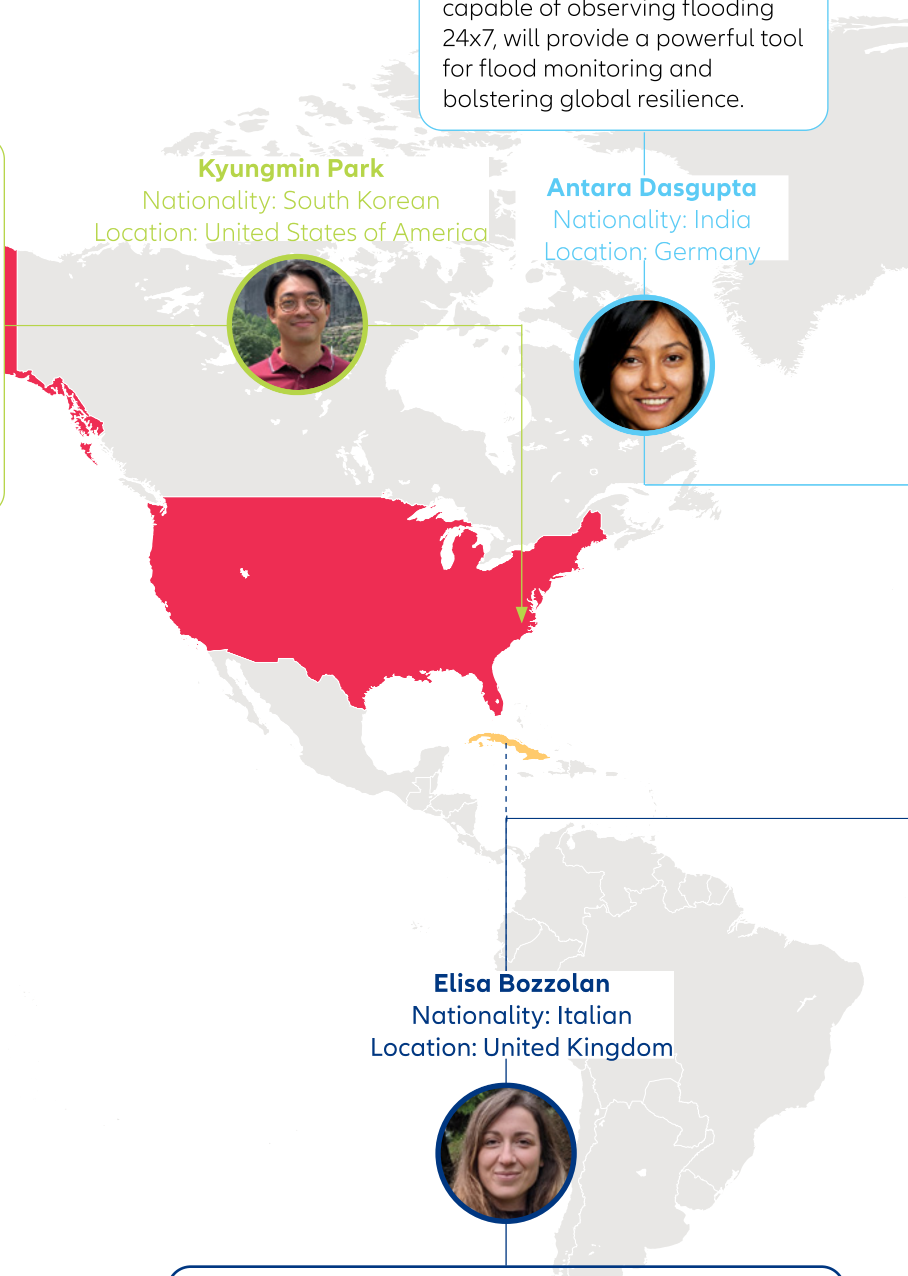
The global sea level has risen about nine inches (24 centimeters) since 1880, with a third coming in the last 25 years. This is due to meltwater from glaciers and ice sheets and the thermal expansion of seawater as it warms. Eight of the world's ten largest cities are near a coast. Higher water levels mean destructive storm surges will push farther inland, threatening infrastructure such as roads, bridges, subways, water supplies and power plants.

Integrating flood mapping with floods models can significantly improve inundation predictions. New research shows that integrating synthetic aperture radars (SAR) on board current generation Earth Observation (EO) satellites, which can penetrate clouds and are capable of observing flooding 24x7, will provide a powerful tool for flood monitoring and bolstering global resilience.



The destructive power of landslides is often underestimated. Annually more than 4,000 people die in landslides, and costs run into the billions of Euros. More frequent and intense rainfall could lead to more landslides, debris flows (rapidly descending earth) and rockfalls. In mountainous areas of Europe and Alaska, researchers have recorded a higher incidence of rockfalls as temperatures rise. In other locations, an increase in extreme rainfall and/or stronger hurricanes – both linked to climate change – can trigger debris flows.

Sources: EPA, EOS, IPCC, NOAA, The Economist, United Nations, USDA

The unpredictable power of water was again highlighted in 2021 when flooding overwhelmed parts of Belgium, Germany and the Netherlands. Climate change will make floods more likely because of more extreme weather patterns. Improved early prediction and warning systems, as well as flood loss modeling, will help limit the damage caused by floods waters and identify and prepare for possible losses.

Smallholder farmers have a hardscrabble existence. Climate change will make their livelihood more precarious. Even moderate increases in temperatures can negatively impact rice, maize and wheat production – the main cereal crops of smallholder farmers. Climate change is also expected to alter pest and disease outbreaks, increase the frequency and severity of droughts and floods, and increase the likelihood of poor yields, crop failure and livestock mortality.

Climate change means extreme heat events are on the rise. Cities, in particular, are subject to increasing temperatures through a heat island effect, which makes the paved environments of urban areas warmer than nearby rural areas. Cooling strategies to reduce Urban Heat Islands can help communities adapt to the impacts of climate change and lower the greenhouse gas emissions that cause climate change.

Climate change affects food security through increasing temperatures, changing precipitation patterns, and greater frequency of some extreme events. In the next 30 years, the food supply will be severely threatened. For example, projections in global yields of both maize and wheat indicate a significant decline. In parts of Africa and Central America, maize is critical in the daily diet of people in the regions. Wheat also plays a significant role, with nearly 700 million metric tons consumed annually.

Climate change affects the physical environment and ecosystems of our planet as well as the societies we have created. This complexity means it is increasingly important to consider how compound events, such as the co-occurrence of extreme weather events, such as heavy rain and strong wind or heatwaves and drought, can have economic, social, and environmental consequences. A developing new generation of climate modelling is gleaning insights into such occurrences by simulating such paired events.

INTRODUCTION WE ARE LIVING IN THE DECISIVE DECADE

HOLGER TEWES-KAMPELMANN
CEO, Allianz SE Reinsurance

Throughout 2021, nature seemed hellbent on physically underlining the grim warnings contained in the latest report from the IPCC. The flash floods in China and Germany, the winter storms that cut power to Texas, unprecedented warm temperatures in the Arctic and the "heat dome" that killed hundreds in North America – all bear the fingerprint of climate change.

The Intergovernmental Panel on Climate Change 2021 report states that such extreme weather results from rising temperatures. And each further fraction of warming will cause ever greater rainfall, higher rises in sea levels and more intense droughts and wildfires. Climate conditions "unprecedented in thousands, if not hundreds of thousands of years," will become more common, concludes the report.

It is clear that we are living through a climate emergency. The adverse effects are already more severe than expected and threaten both the ecosphere and humanity. Failure to slash the amount of carbon dioxide emitted into the atmosphere will make the extraordinary ice melt, heat, storms and wildfires of recent years routine. Ultimately, it will decide whether Earth will continue to be livable.

Science plays a critical role in all of this. First, thanks to the work of scientists who have dedicated their lives to studying climate, we are aware of the dangers of burning fossil fuels. Over more than five decades, increasing numbers of scientists have warned how this threatens to change our planet radically.

Many of the early-stage environmental predictions they foresaw are now felt worldwide. It is also thanks to the efforts of scientists that we are not only informed but that we can – with ever greater accuracy – measure, assess and project the likely devastating consequences.

Finally, apart from helping us understand the climate emergency, scientific research is critical in mitigating the associated risks, delivering rapid decarbonization and assisting communities in adapting to the impacts of climate change.

ANTICIPATING THE RISKS OF THE CLIMATE EMERGENCY

The business of Allianz is to insure risk, but climate change is creating risk on an unprecedented scale. It threatens the livelihoods of hundreds of million people worldwide. It affects the wealth and health of societies. It affects biodiversity, and it affects the value of companies.

Recognizing that climate change will severely impact our business, Allianz integrates climate protection into our core activities. And we systematically consider sustainability criteria in our insurance and investment business.

We also research and analyze the risk profiles of natural perils in all countries where we conduct business. Science is one of the critical tools we have at our disposal. We use it to identify the actual and future impacts of climate change at the regional levels and adapt our risk scenarios. It is essential for us to understand the local risks so we can sustainably insure them.

Further, we use science as a basis to provide risk advice to society and our customers and to increase societal resilience. We share this knowledge by engaging in initiatives with industry peers, providing data to decision-makers and by jointly developing innovative solutions.

BRIDGING THE GAP BETWEEN SCIENCE AND BUSINESS

Yet, there remains a significant gap between climate science and the business world, particularly when implementing the latest academic findings. It is difficult for companies to translate these findings into practical strategies, especially as the business implications are often unclear at local and regional levels.

Allianz Reinsurance has long recognized the need to bring science and insurance closer together. In 2017, we took a significant step to achieve this by launching the Allianz Climate Risk Research Award.

Since then, we have annually recognized promising scientists working in the field of climate risk and natural perils. The award highlights researchers focusing on reducing the risk of extreme weather events that are intensified by climate change, and those fostering resilience by applying technological solutions.

Further, the award assists us in our business. Through the collaboration of young scientists with our Natural Catastrophe (NatCat) department, Allianz better understands the risks and, consequently, is better positioned to advise clients on risk preventive measures.

While we work hard to ensure risks remain insurable, climate change is altering the nature of the risks we cover. The climate emergency is connecting many disasters and worsening them in ways the world is only beginning to understand.

The combination of more frequent and extreme disasters can create situations where insurance policies become too expensive for many customers or impractical for insurers to provide coverage. This means, in the developing climate emergency, preparedness and prevention will become ever more critical in managing risk exposure.

For this reason, Allianz Reinsurance believes more attention needs to be paid to risk awareness and emphasizing the importance of societal resilience. Our main priorities are:

- Encouraging preparedness: for example, through a functioning catastrophe warning system and disaster response capabilities
- Increasing "risk awareness": the public needs simple and easy access to risk information such as flood maps. People unaware of the risk they face will not buy insurance and will not undertake preventive measures to mitigate the impact of the risks
- Investing in prevention: Encouraging the adoption of sustainable and long-term measures to limit the impact of climate change and reduce the overall exposure
- Finally, transferring the remaining risks via the insurance value chain

Within the pages of this Compendium, you will find many ideas from young scientific talents that can contribute to achieving these goals. Like the work of their colleagues highlighted in previous years, these young scientists are contributing to joining the dots on the impact of the climate emergency and helping the world understand and mitigate the complexities of the changes taking place.

FOREWORD RESILIENCE IN A CHANGING WORLD

PROF. DR. MICHAEL KUNZ
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The devastating flood that swept through Germany's Ahr River in July hit residents with full force. The water reached several meters high in places and washed away everything in its path, including buildings, vehicles and infrastructure. More than 180 people lost their lives. The total damage is currently estimated at over €20Bn.

Just weeks earlier, North America suffered a heatwave unlike any recorded before. In Lytton, Canada, temperatures climbed to 49.5°C, exceeding the previous temperature record from 1937 by almost 5°C.

The list of disasters recorded worldwide in 2021 can be extended indefinitely. Of course, individual extreme events cannot be directly attributed to climate change. However, the substantial increase in weather extremes and catastrophes in recent years is an indication that climate change is already taking place and progressing faster than expected.

As part of the World Weather Attribution Initiative, scientists are using elaborate model simulations to investigate the role of climate change in individual extreme weather events. Climate change has significantly increased the likelihood of such severe disasters as those noted above. These two examples also highlight the necessity and urgency of acting now – with measures that include both mitigation, that is, massive reduction in greenhouse gas (GHG) emissions, and adaptation.

UN CLIMATE CONFERENCE

Participants at the 26th UN Climate Change Conference (COP26) in Glasgow are currently negotiating to end the burning of fossil fuels to reduce the global emissions of GHGs. They are also discussing how to financially compensate the countries most affected by climate change but who have only marginally contributed to the climate crisis.

Some commentators have called this conference the "last chance" for a common climate protection policy. Only with a joint and very ambitious climate policy can the Paris Agreement (COP21) aim of limiting global warming to well below 2°C be achieved. However, such ambitious policies are extremely uncomfortable for the main-emitting industrialized countries.

The consequences of failure to limit GHG emissions cannot be foreseen, especially if critical tipping points (such as the thawing of the Russian permafrost or the slowdown in the Atlantic circulation) of the climate system are reached. The insurance industry is expected to play a critical role in reducing GHG emissions.

In addition to a complete transformation to renewable energy in the business sector, a climate-neutral and sustainable investment strategy for assets, solvency capital and individual companies are expected to have a significant impact. The decision of many insurance companies to no longer underwrite commercial and industrial risk for companies in the oil or gas industry, both short- and longer-term, will undoubtedly have far-reaching consequences for the transformation of society towards climate neutrality.

RESILIENT SOCIETY

Natural risks and disasters result from the interaction between extreme events (hazards) and exposed vulnerable objects. Due to climate change, hydro-meteorologically extreme events will further increase in frequency and intensity – but in diverse ways depending on type and region.

Furthermore, societal changes such as increased dependence on and penetration of critical infrastructures, energy transformation or globalization also increase the world's vulnerability to natural and technological risks. External disturbances cascade through various system components and can lead to a complete failure of entire supply and disposal systems. The result is an increase in risk but also an increase in uncertainty and volatility.

Although extreme events cannot, of course, be prevented, the degree of their impact can be significantly reduced. To achieve this, it is necessary to generate sound knowledge about existing and future risks that can be used to develop tools and technologies that increase resilience.

Resilience refers to the ability of a system to continue functioning under stress or to restore its function in the short term. Resilience encompasses both the resistance (ex ante) and the regeneration capacity (ex post) of a system, is adaptive, and allows an appropriate response to even rare, unexpected events (Black Swans).

An essential component of resilience is the risk competency of each individual, which leads to rapid and appropriate actions of the population when a disaster occurs. Acquiring risk competency starts in school but should also be incorporated into the dialogue of different populations and stakeholders – and, of course, in the insurance sector.

The complexity of the processes involved requires holistic, interdisciplinary approaches that can emerge from collaboration between science and industry, as demonstrated by the various projects that are part of the Allianz Climate Risk Research Award 2021. The options briefly discussed above are indispensable to cope with natural or technically induced risks and catastrophic events in the future.

HEARING THE ALARMS

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BIOGRAPHY

Erika R. Meléndez-Landaverde is a Ph.D. candidate at the Center of Applied Research in Hydrometeorology (CRAHI) of the Polytechnic University of Catalonia, Spain. Her research interests compromise disaster risk reduction, impact-based warnings and risk communication during emergencies. Erika is designing and implementing a framework for community-based early warning systems at-risk locations by blending radar-based nowcasting, numerical weather prediction models, and local impact knowledge.

TITLE OF THESIS

Developing a methodology for the design and implementation of site-specific flood warning services (SS-EWS)

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A common factor in the recent devastation caused by floods was that communities and authorities misunderstood or diminished the local risks. Impact-based local warning systems are proving to be far more effective.

As extreme rains turned into catastrophic flooding throughout summer 2021, the world could only watch in disbelief as flash floods and massive landslides cut paths of destruction. From China to Germany, the Netherlands and northeast states in the United States, widespread damage and deaths were reported. As the waters receded, devastated communities were left to deal with the destruction and grief.

Although timely weather warnings about the dire weather conditions were issued by meteorological agencies days ahead of the deluges, a common thread in many cases was that communities and authorities misunderstood or diminished the local risk. As a result, they were caught unprepared to respond and mitigate the impacts. This exposes a critical breach in the emergency management and communication chain.

The Sendai Framework for Disaster Risk Reduction states that Early Warnings Systems (EWS) are crucial for increasing community resilience, especially in the face of climate change. Forecasts have significantly advanced in their capacity and accuracy concerning intense rainfall episodes and their associated impacts (see ANYWHERE-h2020). However, damages and casualties remain high and will continue to increase unless immediate actions support communities to understand better, adapt and deal with the impacts of extreme weather-induced events.

Society is urgently demanding a move towards risk communication centered on communities and their vulnerabilities. This means understandable information on potential local impacts is provided alongside specific and appropriate protection and mitigation actions to reduce the local risk dynamically.

COMMUNITY AND IMPACT-BASED EARLY WARNING SYSTEMS

Impact-based EWS (IBEWS) aim to forecast and communicate the potential consequences regions could observe due to upcoming weather conditions. Although recent technological developments of IBEWS have shown promising results, the next step is to incorporate high-resolution vulnerability and exposure data. This will allow IBEWS to interpret forecasts within a social context and transform them into specific, actionable protective decisions that communities can make during emergencies to reduce their risk.

This is the motivation of the current research: to support communities by empowering its citizens and local authorities to adapt and appropriately reduce the negative impacts of extreme rainfall events using innovative people-centered EWS technologies.

The study focuses on developing a framework for designing and implementing a community-based IBEWS aimed at vulnerable locations or sites within high-risk areas (SS-EWS). The framework blends meteorological information from radar-based nowcasting forecasts (up to two hours lead-time) and numerical weather prediction models (forecasts up to 24 hours) with local vulnerability and exposure information to trigger site-specific warnings (SSWs) for communities and locations in peril.

These SSWs will communicate relevant impacts that could be experienced during rainfall events. They include mitigation actions from pre-defined and approved self-protection plans for citizens and local authorities to dynamically reduce risk during emergencies.

The SS-EWS employs a hybrid participatory approach to capture community needs and integrate detailed vulnerability information into the system. Therefore, the framework's foundation rests in a co-design, implementation and co-evaluation process undertaken with community representatives, emergency responders and local authorities. Additionally, sources of information and technologies, such as social media for validating impacts and mobile applications for disseminating the SSWs, are employed within the SS-EWS framework.

The developed "A4alerts" (see Figure 1) is a tailor-based app designed to connect the SSWs coming from advanced impact-based forecasts and meteorological information with the self-protection plans specific to the community and locations at risk. It provides current active warnings in the area and lists available actions recommended to mitigate the potential impacts of the upcoming weather.

SS-EWS IN THE FIELD

The SS-EWS has been successfully implemented and evaluated across cities at high risk in Catalonia in Spain. The results suggest that the system can trigger SSWs compatible with the reported impacts, but most importantly, activate appropriate pre-defined protection actions to reduce the local risk at vulnerable points with sufficient time.

Additionally, the combination of radar-based nowcasting with NWP allows the system to detect intense rainfall events while monitoring the evolution of the precipitation. Regarding the uptake of SSWs through the app by end-users, initial results suggest that the SSWs trigger more protective actions and are better understood and accepted than current official warnings during extreme rainfall.

PARADIGM CHANGE IN EMERGENCY MANAGEMENT

Recent years have exposed the critical gap between available forecasting tools and mitigation actions undertaken during emergencies. If not immediately addressed, stories of avoidable catastrophic situations and significant losses will – exacerbated by climate change – continue to grow to an unimaginable scale.

The community-based SS-EWS framework shows promising results in playing a central role in promoting a shift towards resilient societies that understand their vulnerabilities. Further, it can help them adapt to upcoming changes and ensure they are prepared to respond effectively to reduce the potential impacts due to extreme rainfall events.

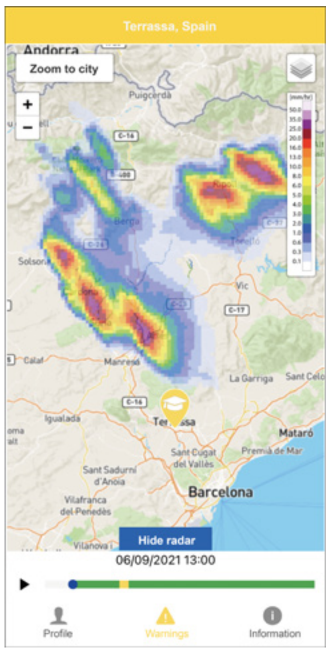

Figure 1: *The "A4alerts" tailor-based emergency app*

GAUGING WATER LEVEL RISES USING SMART TECH

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BIOGRAPHY

Kyungmin Park is a Ph.D. candidate in the Ocean Science and Engineering program at the Georgia Institute of Technology. Using multidisciplinary knowledge and skills, he has developed and deployed a high-resolution model on the US southeast coast. Collaborating with governments, Kyungmin has helped coastal communities to make data-driven decisions for risk assessments, coastal protection and evacuation plans.

TITLE OF THESIS

Development of Coupled Model for Coastal Risk Assessment

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Tide gauges are sparsely installed, which is a problem if we want to understand the emerging threats from sea-level rises. Modern technology means inexpensive internet-enabled sensors and a city-scale model can be placed far more frequently for more detailed analysis on water levels.

Coastal cities and communities are on the frontline as climate change swells oceans and redraws maps. Yet, despite the emerging threats of sea-level rise and flooding, water level observations along most coasts are inadequate and rely on sparsely located tide gauges.

For example, the National Oceanic and Atmospheric Administration has only one tide gauge installed on the Georgia coast in the United States, although the area experienced the highest water level on the southeast coast during hurricanes Matthew (2016) and Dorian (2019). The lack of tide gauges means it is impossible to capture the spatial variation in water level associated with extreme events.

Consequently, little is known of the underlying drivers of flooding in the rivers and creeks around residential areas. These limitations pose challenges for understanding, predicting and mitigating the regional and city-scale impacts of natural catastrophes and climate-related coastal floods. They also mean policymakers and insurance companies cannot make data-driven decisions.

HIGH-RESOLUTION MODELING AND WATER SENSING

In this research project, high-density water level sensors and a city-scale resolution model is developed to monitor and analyze detailed information on water levels. The Smart Sea Level Sensors (SSLS) project installed internet-enabled sensors at an affordable cost in the City of Savannah, Georgia, and its surrounding counties. The installations stretch from the coast to inland waterways (Figure 1 a)

The data collected is complemented by a high-resolution (approximately 10 meters) coastal ocean model. This model can capture multiple drivers such as tide, large-scale ocean circulation, wind, atmospheric pressure, precipitation, and river discharge to reproduce extreme water levels accurately.

Until now, large-scale forecast models of inundation had a coarse resolution of approximately eight kilometers. This meant they could not deliver spatial information at the scale where people live and make decisions as water levels in the waterways, creeks and wetlands typically have widths varying from tens to hundreds of meters.

The developed model uses a flexible grid system to efficiently resolve the complex shapes of creeks, lakes and rivers. This novel framework enables unprecedented assessments of short- and long-term coastal risk and vulnerability for coastal protection planning.

UNDERSTANDING AND PREDICTING FLOOD DRIVERS

The model and SSLS observing network (Figure 1 b) are advancing understanding of floods and the ability to prepare for extreme hazards. For example, analysis of historical events reveals that, in addition to high wind speed, oceanic adjustment by hurricanes (for example, shelf scale waves and changes in the Gulf Stream) contribute significantly to determining storm surge around the residential area.

After a hurricane dissipates, the oceanic drivers can again increase the water level above the average of the highest tide level for days, a phenomenon known as "sunny day floods." This gives new insight into the relative role of flood drivers along the US southeast coast.

Furthermore, the model provides three-day forecasts for a coastal community, including an early warning system. When hurricanes Dorian (2019) and Isaias (2020) passed over the US east coast, for instance, the system predicted the peak timing, level and duration of the storm surge during the transit of the hurricanes. This meant the resulting water damage could be reasonably predicted, which helped stakeholders and Chatham Emergency Management Agency (CEMA) better prepare for these hazards on the Georgia coast.

CONNECTING RESEARCH TO COASTAL SOLUTIONS

The results from this project serve as the foundation for co-designing a set of coastal solutions strategies with local decision-makers. This includes forcing scenarios to examine how urban flood risk depends on uncertainties related to future changes in the climate and human drivers for emergency preparedness and urban planning.

Given that the Georgia coast is representative of coastal communities along the US southeast coast, this flood modeling and analysis tool is applicable in other coastal cities as it advances our fundamental understanding of urban flood dynamics. The lessons learned from this research will provide critical data needs and best practices to scientists, engineers, policymakers and insurance companies.

Figure 1: a. *The model domain with bathymetry and the locations of total SSLS (green circle) and selected sensors (orange circle) for model validation.*

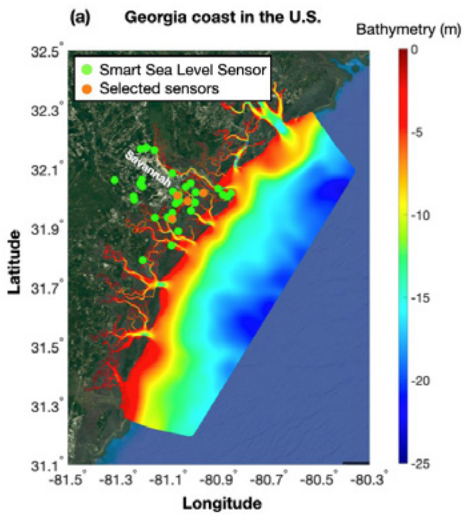
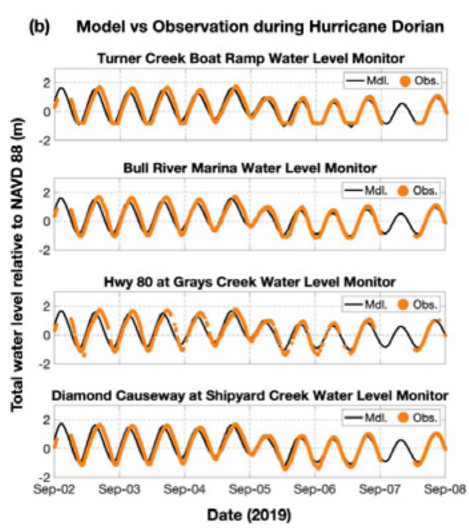


Figure 1: b. *The comparison of total water levels between model and observations during Hurricanes Dorian (2019) at the locations of the selected sensors.*



WHY ARE CITIES SO WARM?

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Born and raised in Nigeria, Henry is a joint Ph.D. researcher in Future Cities Engineering at the Institute of Infrastructure and Environment (IIE) of the University of Edinburgh and the Urban Big Data Centre (UBDC) of University of Glasgow. An Erasmus scholar, Henry obtained triple Masters (Distinctions) in Urban Climate and Sustainability from the Glasgow Caledonian University, UK; LAB, Finland; and Huelva, Spain. He holds a Bachelor of Technology in Meteorology from FUT Akure, Nigeria. His research is focused on mitigating Urban Heat Island effects in future cities with sustainable earth building materials. Henry manages SustyClimateHub.com, an online platform he founded to share global opportunities within climate and sustainability in his spare time.

TITLE OF THESIS

Improving Liveability in Future Cities with Sustainable Earth Building Materials: A multi-scale study

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Urban heatwave is one of climate change's deadliest – but overlooked manifestations. How can cities defend against it?

Back in 2018, the Netherlands experienced two heatwaves over three weeks where around 300 more people died than would normally be expected at that time of year. This was dismissed as a "minor rise" by officials. If those people had been killed in floods, it would have been front-page news for weeks.

Heatwave disasters do not get the attention they merit for several reasons. Deaths tend to be more widely dispersed and gradual. At the same time, heatwaves do not have the property devastation caused by the ravages of wind and water. Yet, globally, according to the World Health Organization, more than 166,000 people died due to heatwaves from 1998-2017. The most prominent is the 2003 summer heatwave that ravaged Europe, killing over 70,000 people.

URBAN HEAT ISLANDS

Unfortunately, extreme heat-related disasters are expected to increase in intensity, frequency and duration due to changing climate. This year a study found that 37% of heat-related deaths could already be linked to climate change. One of the main contributors to climate change is rapid urbanization. Projections show that by 2050, urban dwellers will increase from 55% to 68% of the global population.

This presents enormous challenges for human well-being. First, urbanization means natural surfaces are converted into built-up structures that alter the thermal dynamics of the immediate environment. Second, urbanization is often accompanied by densification. This increases the number of occupants of structures without increasing their footprint. This is seen in expanding cities, where suburban dwellings are often replaced with duplex houses or low-rise apartment blocks to meet housing demand.

The outcome is Urban Heat Island (UHI) – regions of increased temperature due to occupancy. This phenomenon results in urban centers and central business districts (CBDs) that have significantly higher temperatures when compared with rural outskirts (Fig 1). Depending on the region, increased heat can also increase the air conditioning requirements, which generates more heat, creating a vicious cycle.

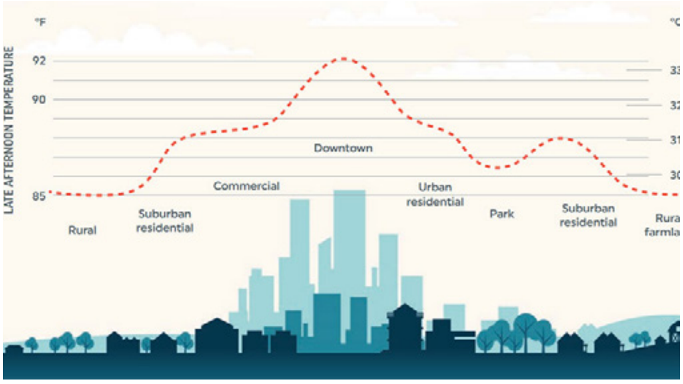

Fig 1: *The Urban Heat Island Profile (ULI, 2020)*

THE CAUSE OF URBAN WARMING

Cities are becoming warmer because of the ever-changing urban morphology. The characteristics of urban areas, such as the building materials, urban geometry or orientation and land-use zoning, including the amount of green space, all contribute to the urban thermal composition. These all have consequences on the intensity of urban warming.

The problem is how to mitigate urban warming? Since most cities are already built-up, little can be done to change urban geometry, especially in the center, where there are limited spaces to add more green areas. However, significant improvements can be achieved with building materials. Although we cannot entirely change existing building materials, we can add external façades to improve indoor thermal and energy efficiency.

LOOKING TO ANCIENT TECHNIQUES

For centuries, ancient architects and builders have relied on the thermal efficiency of earth materials (earthen bricks, rammed earth etc.) for building construction. These earth materials have significant thermal properties and present a low-embodied carbon alternative to conventional cement construction.

This research investigates the extent to which cement building materials can be replaced with thermally massive earthen materials. By doing so, we can mitigate emerging UHI effects and alleviate the need for energy-intensive air conditioning.

BUILDING WITH THE EARTH

To identify the benefits of earth materials for mitigating UHI in cities, multiscale research was conducted. The evaluation comprised market research, urban energy simulation, urban microclimate modelling and cost-benefit analysis components. The market research identified the range of materials available for dwelling construction in hotter climates (such as Perth, Australia and Arizona, USA), for example, low embodied energy earthen materials.

Energy simulation was modeled at the dwelling scale. Urban microclimate and human thermal comfort simulation were modeled at the neighborhood scale. City scale analysis will be evaluated using high-resolution remote sensing data to examine the interconnectivity between these systems.

The multiscale challenge was addressed by combining state-of-the-art urban microclimate and thermal comfort modelling (ENVI-MET), structure energy use simulation (EnergyPlus), and remote sensing. These were validated by real-world climate data capture and indoor climate sensor networks to ensure the quality of the analysis.

The simulations captured current performance and future climate change scenarios for the earthen materials chosen to envelop structures. The modeling was supported by laboratory testing to identify steady-state and transient earth material properties.

DESIGNING WITH URBAN ENERGY PERFORMANCE IN MIND

The idea behind the research is that new dwellings should be designed with their energy performance in mind. They should also consider how their performance will influence structures around them and the nearby urban microclimate. The outcome will contribute towards achieving the UN sustainable development goal (SDG) 11 of ensuring a sustainable city for all.

TACKLING DEADLY URBAN LANDSLIDES IN A CHANGING CLIMATE

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BIOGRAPHY

Elisa Bozzolan is a postdoctoral researcher at the University of Bristol (UK), where she is part of the water management research group. Elisa's research focuses on designing innovative scientific tools to support engineers and policymakers in natural hazard risk reduction. This work builds on her Ph.D. research, during which she developed a new scientific methodology to identify the best landslide hazard mitigation measures within informal settlements in Saint Lucia (Caribbean). This new methodology allows quantification of uncertainty (including climate change) and can assess the impact of different hazard mitigation options with transparency. She uses the same methodology to advise Arup, a consultancy firm, on the impact of different hazard mitigation policies in Freetown (Sierra Leone).

TITLE OF THESIS

Quantifying the influence of informal housing on rainfall-triggered landslides in the humid tropics

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Assessing landslide risk can be difficult under changing environmental conditions. We require new tools to better understand how such changes can affect landslide probability to then identify the most effective landslide mitigation policies.

One of the 21st challenges is reconciling booming global urban growth with the prevention and mitigation of environmental disasters, such as those caused by landslides. When landslides occur near populated areas, they pose a significant hazard to people and property.

Globally, 300 million people are exposed to landslides. This results in more than 4,000 fatalities annually, with an extra 250,000 people affected. The annual cost in economic damages is 4.7 billion Euros in Europe alone.

In the future, the impact of landslides might be worse for two reasons. First, severe precipitation, such as rain, sleet or hail, is expected to become more frequent under climate change, causing more rainfall-triggered landslides. Second, the growing urban population will lead more people to live in areas exposed to landslides globally, particularly in developing countries where low-income dwellers tend to overcrowd landslide-prone areas, such as steep slopes.

In tropical regions, hurricanes are expected to increase in severity and regularity. This, plus increasing urbanization, means understanding where and when landslides might occur is becoming increasingly crucial.

CURRENT PREDICTIONS ARE TOO UNCERTAIN

One method used to predict future landslides is to look at the past. Analysis of historical records allows hillslopes that have failed in the past to be identified. Currently, stable hillslopes with similar conditions (for example, similar slope gradients) are "tagged" with high landslide probability. Such areas are typically excluded for construction development or might be the first alerted when severe precipitation is expected.

However, this approach to landslide prediction is often insufficient. Landslides and rainfall records, as well as data on hillslope properties, are often affected by significant errors or lack sufficient detail. In addition, what happened in the past might not represent what may happen in the future, making historical records less useful for long-term projections.

Climate and socio-economic models can be used to build scenarios of how rainfall patterns and cities might look like in the future. Unfortunately, these models depend on highly uncertain factors, such as future carbon emissions, so that the future scenarios predicted can vary significantly one from the other. As a result, landslide estimates can be extremely different and sometimes contradictory – some may predict an increase in landslides and others a decrease – undermining their practical use for risk management.

FROM "PREDICT THEN ACT" TO "ACT NOW WITH LOW REGRETS"

Instead of predicting how climate and urban expansion will evolve in the future, this research used a different approach centred on decision making. I asked the question: how much climate and/or urban development needs to change before landslide hazard significantly increases?

The scientific method behind the analysis (Bozzolan et al. 2020, NHESS) first generates thousands of synthetic but realistic hillslopes representations of the study area. Then it imposes hypothetical scenarios of increasing rainfall severities and urban expansion. It also considers different construction features that could affect slope stability (for example, the presence or absence of roof gutters on houses).

Finally, it uses a computer model to assess the stability of these virtual hillslopes, generating a new synthetic library of landslide records. By exploring the library, it is now possible to identify the combinations of rainfall and urban development conditions (for example, with or without roof gutters) most likely to cause hillslopes to fail.

"Low-regret" mitigation actions will be those actions that perform well across scenarios and, therefore, should be prioritized even if future rainfall and urban predictions remain unknown.

A PRACTICAL TOOL FOR DECISION-MAKERS

This new method explores many "what if" scenarios making it a valuable tool for decision-makers tackling landslide risk management and reduction. For example, figure 1 shows how a map of landslide probability in Saint Lucia (Eastern Caribbean) might look like if the severity of a destructive rainstorm, such as the 2010 Hurricane Tomas, increased under climate change or unregulated housing expanded on slopes susceptible to failure.

The analysis also shows that landslide probability disproportionally increases when both scenarios are included, revealing that "the whole is greater than the sum of its parts." This information could be used to assess the risk and damages associated with each scenario and to identify low-regret nation-wide risk reduction and risk transfer strategies.

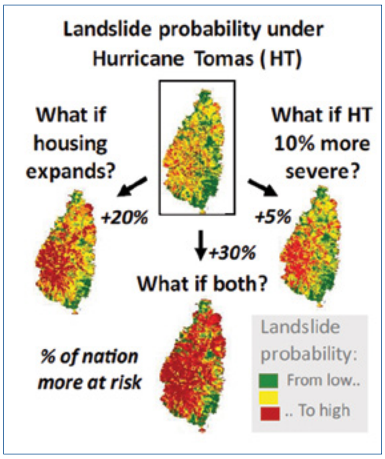

Figure 1: *Maps of landslide probability in Saint Lucia under different "what if" scenarios. The percentage (+%) indicates the increase of areas with high landslide probability.*

The same method can also be applied to quantify the cost-benefit ratio of different landslide mitigation options, such as improving urban drainage or tree planting at the community/household scale. In Freetown (Sierra Leone), for example, I collaborated with Arup, an engineering firm, to identify which and where landslide hazard mitigation actions would lead to the largest reduction in landslide probability so they could be prioritized.

The information generated through this analysis not only provides evidence to governments and investors for informing urban planning, but it might encourage micro-insurance in disaster prevention, where insurers offer lower premiums to reward risk-reducing behaviours.

THE FUTURE IS FLOODED

AUTHOR
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INSTITUTION

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BIOGRAPHY

Antara Dasgupta is a postdoctoral research associate at the University of Osnabrueck, Germany, exploring the role of deep learning in hydroinformatics and remote sensing to bolster global flood forecasting capabilities. Previously, she evaluated commercial radar satellite data capabilities for flood monitoring and developed radar-based flood mapping algorithms as the Senior Radar Scientist at Cloud to Street PBC, USA. She earned a dual-badged Ph.D. degree in Civil Engineering from the Indian Institute of Technology Bombay and Monash University in 2020. She was awarded the excellence in Ph.D. research award by both institutes. Antara has worked on monitoring and modelling floods across the globe, including Australia, Ghana, India, Morocco and Mozambique. In 2021, her contributions to spatial sciences were recognized through the SSSI Postgraduate Student of the Year Award for Australia and New Zealand by the Oceanic Asia-Pacific Spatial Excellence Awards (APSEA). Recognized as one of the Rising Stars of Asia – Women in Engineering by the Asian Dean's Forum in 2019, Antara is passionate about improving global flood resilience through technological innovation and increasing the representation of women in STEM fields.

TITLE OF THESIS

Optimizing SAR-based Flood Extent Assimilation for Improved Hydraulic Flood Inundation Forecasts

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Earth Observation radar satellites have the technology to penetrate clouds and observe flooding 24x7, providing an indispensable tool for flood monitoring. We need better solutions to tap into the latent ability.

Haunting images that went viral during the July floods in Belgium, Germany and the Netherlands highlight the threat of climate change to even the best-prepared and advanced economies. Belgium and the Netherlands are renowned for sophisticated systems of dykes and canals. Yet, mud and water flowed through the streets a meter deep in some parts of the Netherlands.

In Germany, whole towns were inundated, and evacuation failed, weather forecasts, indicating extreme rainfall, being available days in advance. *Der Spiegel*, a leading German magazine and news website, reported that the local government lacked the technical knowledge to interpret the forecast implications fully.

This failure is partly due to a critical gap in current forecasting systems, which provide either rainfall predictions or point-based river flow forecasts that are difficult to interpret by local decision-makers. When determining time-sensitive preparedness initiatives like large-scale evacuations, high-resolution spatial flood risk information and uncertainty estimates are vital to confident decision-making.

Flood maps showing which areas should be evacuated are an important first step in providing clear information to decision-makers and stakeholders. This research focused on interpreting satellite images into probabilistic flood maps and integrating them with physical flood models to reduce uncertainties in spatial inundation forecasts.

OBSERVING FLOODS FROM SPACE

Synthetic aperture radars (SAR) on board several current generation Earth Observation (EO) satellites can penetrate clouds and are capable of observing flooding 24x7, providing an indispensable tool for flood monitoring. Due to the sensitivity of the observed radar returns to Earth surface properties and sensor characteristics, the reliability of the flood maps strongly depends on these attributes.

Hence, it is imperative to quantify the accuracy of the maps and communicate the associated uncertainty. To solve this problem, a novel probabilistic sensor-independent algorithm that exploits the inherent spatial patterns in the radar data along with the returns was developed.

Incorporating the strength of spatial pattern recognition within the algorithm led to a 54% improvement in accuracy over the use of radar surface returns alone, with maximum error reductions over sparsely vegetated and grassland covered areas. While reliable flood mapping from SAR is an essential tool for emergency management, the key to increased flood resilience lies in integrating them with flood models to improve inundation predictions.

PREDICTING FUTURE FLOODS

Any predictions rely on mathematical modeling, but perfect models do not exist. While flood models aim to provide a realistic representation of future risk to promote climate resilience and reduce the overall cost of disasters, uncertainty in the inputs and parameters often leads to erroneous flooded area predictions.

Uncertainty-aware model-data integration of the "flood" of data continuously recorded by EO satellites has the potential to mitigate these errors and lead to more accurate forecasts over longer prediction horizons. Typical solutions to this approach attempt to derive information about flood variables not (yet) directly observable by satellites, such as flow depth, leading to high prediction uncertainty.

As part of the research, the PF-MI approach that directly combines satellite-derived probabilistic flood extent maps with mathematical flood models was developed using state-of-the-art techniques. Exploiting the potential of information theory, this algorithm surpassed the performance of state-of-the-art approaches by achieving a significant reduction in errors and longer persistence of forecast improvements. The forecast quality was improved for lead times of more than a week, which could mean the difference between life and death for many people in the path of flooding.

Additionally, in the tested cases, the accuracy of the spatially forecasted flood depth was improved by more than 70%, highlighting the algorithm's potential to be adopted by the insurance industry for parametric payouts. Furthermore, the importance of the satellite observation configuration in space and time was revealed, highlighting the possibility of further optimizing the model-data integration approach.

LEVERAGING THE "FLOOD" OF DATA

There are currently over 900 active EO satellites, many of which can be tasked to capture images with tailored location, timing and frequency to support specific applications. Since new generation high-resolution satellites can only observe small portions of large rivers and model-data integration is sensitive to observation characteristics, targeted observation strategies can and must be developed to maximize forecast improvements.

Using a novel experimental strategy, the relative value of observation characteristics in space and time was quantified to optimally utilize the power of satellite tasking. The model-data integration proved extremely sensitive to the observation location concerning the river network and floodplain geometry and with respect to the timing relative to the arrival of the flood wave.

A single optimally acquired image resulted in improvements in flooded area predictions comparable with the integration of multiple sub-optimally located and/or timed images. This study laid the groundwork for an automated satellite tasking system, which could optimize the cost-benefit of application-specific satellite acquisitions.

The future is flooded, but technological innovation has the power to bolster global resilience to its disastrous consequences. This study provided the first step in combining state-of-the-art satellite technologies, computer science and mathematical modelling to fight catastrophic flooding and save lives.

WHEN HEAT BECOMES DEADLY

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BIOGRAPHY

Eunice Lo is a climate scientist at the School of Geographical Sciences and Cabot Institute for the Environment at the University of Bristol. Her research combines climate observations, climate model simulations and epidemiological models to assess the impacts of extreme temperatures on human health. Eunice has published widely on heat and health, and she is leading research development in other aspects of climate change and health by organizing workshops and forming new collaborations.

TITLE OF THESIS

Quantifying the heat-mortality impact of climate change

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Extreme heat in western North America this summer is a stark reminder of the health impact of climate change. Until recently, future extreme heat-related mortality in American cities associated with 1.5, 2 and 3°C global warming was unknown.

Heatwaves turned large parts of North America into a furnace last July, killing hundreds of people in Canada and the United States. The BBC reported that 486 fatalities were recorded in British Columbia over five days, a 195% increase on the usual amount over that period.

Increases in the intensity, frequency and duration of heatwaves are well-known consequences of man-made climate change. Extreme high temperatures can increase human morbidity and mortality, as evidenced by the high death tolls of historic heatwaves. One notorious example is the 514 excess deaths associated with the 1995 Chicago heatwave.

In recent years, scientists have started to combine statistical health models with climate models to estimate the heat-mortality impact of climate change. However, until the publication of my research (Lo et al., 2019), studies were based on scenarios like the Representative Concentration Pathways (RCPs) or predecessors, rather than policy-relevant scenarios representing the 1.5 and 2°C temperature targets in the Paris Agreement.

My research was the first to use dedicated large ensembles of climate simulations to compare the heat-mortality impact in American cities between these Paris Agreement targets and 3°C warming. This level of global warming is estimated to be consistent with current climate policies.

Quantifying this is important because it can inform mitigation discussions in major climate conferences such as the United Nation's COP26. It can also provide insurers with evidence to devise health insurance premiums that are ready for the changing demands of a warming climate.

DEDICATED 1.5, 2 AND 3°C LARGE ENSEMBLES

In my 2019 paper, 90-member ensembles of daily temperature simulations were utilized in three dedicated climate scenarios — 1.5, 2 and 3°C global average temperatures above pre-industrial levels. These scenarios are part of "Half a degree Additional warming, Prognosis and Projected Impacts" (HAPPI), a project specifically designed to study the differences in extreme weather and their impacts between the Paris Agreement targets.

Added to the original HAPPI, the 3°C scenario was designed so the impacts of the "current policies" scenario could be compared against 1.5 and 2°C warming. This scenario has since been used in another study that I co-authored (Shiogama et al., 2020).

With each member differing in its initial perturbation, the large ensembles were designed to capture internal climate variability and temperature extremes. In the 15 studied American cities (Figure 1), it was found that the average hottest monthly temperature, or TXx, in the 2°C scenario would be up to 1°C warmer than that in the 1.5°C scenario. TXx over the cities would be up to 1.8°C warmer in the 3°C scenario than the 2°C scenario. Extreme heat over the cities is projected to warm more than the global average temperature.

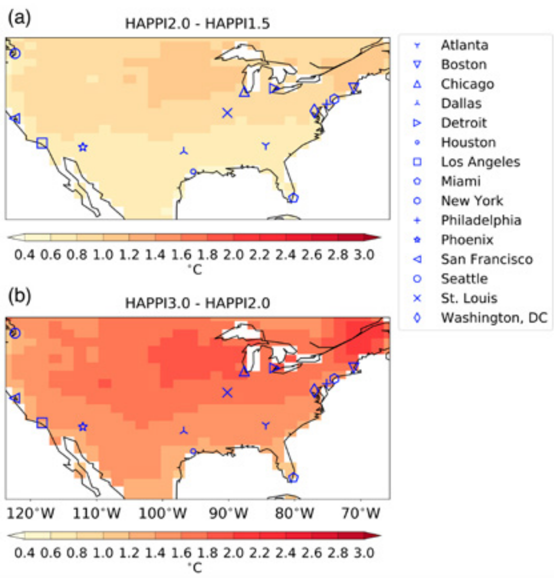

Figure 1: *TXx differences between the (a) 2 and 1.5°C scenarios, and (b) 3 and 2°C scenarios.*

THOUSANDS MORE HEAT DEATHS PER CITY

The heat-related mortality associated with a 1-in-30-year heat event in each city and climate scenario was quantified. This was achieved by combining temperature-mortality relationships derived from the cities' observed temperatures and mortality counts with the above climate simulations.

Depending on the city, 34 (in Atlanta) to 736 (in New York City) more heat-related deaths were projected for 1-in-30-year heat events in the 2°C warming scenario, compared to the 1.5°C scenario. Under the 3°C scenario, 114 (in San Francisco) to 2716 (in New York City) more 1-in-30-year heat deaths were projected than the 1.5°C scenario (Figure 2). Following the "current policies" trajectory could result in thousands of more heat-related deaths per city during extreme events.

In Chicago, in particular, events like the 1995 heatwave would become significantly more likely because of climate change: about once every five years in the 1.5°C scenario, once every three years in the 2°C scenario, and twice every three years in the 3°C scenario. What was once a rare, extreme event is expected to become the new normal.

MITIGATION AND ADAPTATION CAN SAVE LIVES

Cutting greenhouse gas emissions to meet the 1.5°C target could prevent hundreds to thousands of annual heat-related deaths per American city during extreme events. This research provides evidence for the health benefits of mitigating climate change.

Moving from long-term climate change to the near term, my current research focuses on monitoring and predicting heat-related mortality. I am collaborating with UK Health Security Agency and the Met Office to develop frameworks that monitor the health impacts of heatwaves in near real-time. The aim is to alert the public and the health and social care sector to potential health impacts when a heatwave is forecast. This research helps national agencies adapt the population to rising temperatures, which is necessary in conjunction with mitigation.

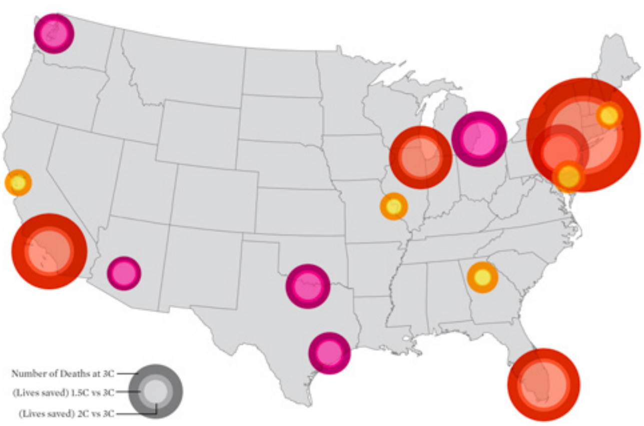

Figure 2: *1-in-30-year heat deaths in the studied cities in (outer circle) the 3°C scenario, and the difference in deaths between (inner circle) 1.5°C and 3°C, and (innermost circle) 2°C and 3°C. A larger circle indicates a higher number of deaths*

UNDERSTANDING HOW CLIMATE CHANGE THREATENS FOOD SECURITY

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BIOGRAPHY

Thong Nguyen-Huy is a Postdoctoral Researcher at the Centre for Applied Climate Sciences, University of Southern Queensland, in Australia, where he obtained his Ph.D. in Applied Mathematics and Statistics in Climate and Agriculture in 2019. He is also employed at the Drought Resilience Adoption and Innovation Hub" at the Centre for Applied Climate Sciences at the SQNNSW. Thong's research interests include modelling and data analysis, developing and applying novel statistical models, AI algorithms and remote sensing techniques. He works closely with researchers, governments, insurers and financial institutions on agricultural resilience, climate risk and alternative risk transfer systems. He has published widely in the fields of climate, agriculture, environment, hydrology, energy, and risk management.

TITLE OF THESIS

Copula-based statistical modelling of synoptic-scale climate indices for quantifying and managing agricultural risks in Australia

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Analyzing the challenges extreme climate events pose to food systems based on a single driver could underestimate the risks because of the interaction among extreme events across multiple spatial and temporal scales.

The 2021 Intergovernmental Panel on Climate Change report links rising global temperatures over the past century, increases in the number and severity of storms, and worsening droughts and floods to a decrease in food security. Future changes in temperatures, increases in floods and droughts and more pests and diseases will further affect the food supply and lead to higher risk for all aspects of the food system.

For example, despite farmers' efforts to adapt to changing conditions, wheat yields in India fell 5.2% between 1981 and 2009 — while the population grew by 66%. More recently, heavy rains have produced swarms of locusts across East Africa and Southwest Asia, destroying crops and disrupting food supplies.

The increasing effects of climate change are likely to decrease rice, corn, wheat, and soy — the four essential crops upon which the world depends.

Existing research seeking to understand the impact of climate change tends to focus on a single driver. However, interactions between extreme events may increase the climate influence. Analyzing the challenges that extreme events pose, for example, to food systems, based on a single driver could lead to underestimating risk because of the interaction among extreme events across multiple spatial and temporal scales.

Only a few studies have investigated the combined impacts of multiple climate drivers using multivariate models with some assumptions restricted in practice. The lack of research and approaches to completely model the interdependence between climate drivers obstructs effective risk-based assessment, management and adaptation.

The spread of extreme events over locations and times, known as systemic risk, is also a significant obstacle for implementing risk transfer solutions such as crop insurance products because of weak modelling of the relationship between events.

CO-OCCURRENCE OF EXTREME EVENTS ENHANCES IMPACTS

This research project developed a vine copula-based model to quantify the joint influence of El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) on seasonal rainfall in Australia using (Nguyen-Huy et al. (2017). "Copula-statistical precipitation forecasting model in Australia's agro-ecological zones." *Agricultural Water Management*). The results show that considering the interactions between two climate indicators, Southern Oscillation Index (SOI) (for ENSO) and Tripole Index (TPI) (for IPO), improved the rainfall forecast in the east and southeast regions. This was particularly true during the co-occurrence of an extreme positive SOI (La Niña) and a negative TPI.

The co-occurrences of extreme events of SOI and the Indian Ocean Dipole (IOD) were also found to enhance the climate influence on wheat crops in Australia (Nguyen-Huy et al. (2018). "Modeling the joint influence of multiple synoptic-scale, climate mode indices on Australian wheat yield using a vine copula-based approach." *European Journal of Agronomy*).

The developed vine copula-based model, relative to conventional linear regression, provided a better description of the joint distribution between multiple variables, particularly the tail dependence when the extreme events occur together. This characteristic is also beneficial for analyzing stochastic dependence of systemic weather risk, such as when extreme events cover a large area, which is a major impediment for developing private (non-subsidized) crop insurance.

BETTER UNDERSTANDING OF SYSTEMIC RISK REDUCES INSURANCE LOSS

With weather-related insurance, particular attention is paid to quantifying the probability of significant large claims for indemnities made when unfavorable weather events occur at the same time at different places. Therefore, for an insurance company, it is important to estimate a sufficient buffer fund (BF) as a reserve to handle indemnity payments and avoid bankruptcy during widespread systemic losses.

We applied a C-vine approach to model the joint insurance losses caused by drought co-occurring across multiple locations and consecutively in different growing seasons (Nguyen-Huy et al., (2019). "Copula statistical models for analyzing stochastic dependencies of systemic drought risk and potential adaptation strategies." *Stochastic Environmental Research and Risk Assessment*).

The results indicated that the average risk-reducing effect of the entire insured area across regional, national and temporal scales ranges between 0.62–0.94, 0.48–0.76, and 0.25–0.33, corresponding to 5%- (extreme drought) and 25%-quantiles (moderate drought). Thus, the research can be an efficient tool for agricultural risk reduction and pricing weather index-based insurance products. The findings suggested that spatial and temporal diversification strategies could feasibly reduce the systemic weather risk in Australia.

OPTIMIZING RETURN-RISK TRADE-OFF IN SPATIAL DIVERSIFICATION PORTFOLIO

We proposed a new statistical approach that combines copulas and Conditional Value-at-Risk (CVaR), a robust downside risk measurement in finance, to evaluate the effectiveness of spatial diversification for wheat-farming portfolio management (Nguyen-Huy et al. (2018). "Copula-based agricultural conditional value-at-risk modelling for geographical diversifications in wheat farming portfolio management." *Weather and Climate Extremes*).

CVaR is used to benchmark the loss, while the copula function models joint distribution among marginal returns. The results of mean-CVaR optimizations indicate that spatial diversification is a feasible agricultural risk instrument for wheat-farming portfolio managers in achieving their optimized expected returns while controlling risks (that is., targeting levels of risk).

For example, by allocating 10% of their production area to the state of Victoria, wheat producers in South Australia can adjust expected profitability in the worst 5% of cases from approximately 33.98% to 33.69% (a reduction of 0.29%). This can reduce downside risk from approximately 14.70% to 11.51% (a risk reduction of 3.19%). Furthermore, the copula-based mean-CVaR model yields better simulation of extreme losses than traditional multivariate-normal models, which underestimate the minimum risk levels at a given expected return target.

The research also investigated whether integrating spatial diversification and climate information could minimize climate risk, while not sacrificing profitability for grazing enterprises (Nguyen-Huy et al., (2020). "Integrating El Niño-Southern Oscillation information and spatial diversification to minimize risk and maximize profit for Australian grazing enterprises." *Agronomy for Sustainable Development*).

The research framework applies to other parts of the world and could provide value-based information for agricultural risk reduction and insurance solutions.

COMPOUND EVENTS IN THE PAST, PRESENT AND FUTURE

AUTHOR

Nina Ridder

INSTITUTION

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BIOGRAPHY

Nina Ridder is a Research Fellow at the ARC Centre of Excellence for Climate Extremes, University of New South Wales, Australia. Her work focuses on compound climate and weather events. She has generated the first global climatology of observed compound events. She has also identified regions particularly at risk from a variety of these events in the future to show how lower emissions futures bring benefits in protecting communities. Nina is actively promoting the inclusion of the multivariate nature of many high-impact events into existing risk assessment techniques and raising awareness for this need with government organisations, the private sector, and relevant stakeholders.

TITLE OF THESIS

Compound events in the past, present, and future

Compound events – events during which two weather or climate-related hazards co-occur – can have devastating effects. Knowing where and when these events occur and how their incidence is affected by climate change is central to mitigating risk for insurers. This work assesses where different types of compound events occur, how accurately global climate models can simulate them and what compound events will look like in the future.

Extreme weather and climate events often result from a combination of multiple hazards or drivers. For example, storm damage is caused by a combination of wind, heavy rainfall and, in coastal areas, elevated sea levels due to storm surges and high waves – all generated by the same synoptic system.

In 2020, damage from storms caused global economic losses of US$92.7 billion. Similarly, co-occurring heatwaves and droughts, which are often physically linked, have the highest fatality rate of any natural disaster and can act together to condition regions for devastating wildfires, as seen in Australia, South America and the United States in 2019/2020.

Traditionally, risk assessments commonly assume each extreme to be independent of all others. However, questions such as "what is the risk of extreme rain?" or "how likely is a heatwave?" miss the connection of extremes and the compounding impact of co-occurring events. This leads to an underestimation of actual damages caused by storms and their likelihood of occurrence (see the work of Ridder et al., 2018; van den Hurk et al., 2015; Zscheischler et al., 2018).

AN EMERGING NEW SCIENCE

Compound event research has emerged to address the science and risk of co-occurring hazards that often share common causes and affect a region simultaneously. While many possible types of compound events threaten human systems, our knowledge of where and when they occur or how they might change in the future is limited.

This research focuses on addressing these limits with the goal to reduce the risk humans are exposed to. In undertaking the research, it was first necessary to determine which regions are prone to compound events and the type of events experienced.

To achieve this, the first global climatology of compound event occurrence likelihood was generated. The blending of high-quality observations with reanalysis data for wind-related hazards for the period 1980–2014 demonstrated which regions were vulnerable to which compound events on a seasonal timescale.

The research showed that prolonged heat in combination with low precipitation dominated almost all assessed geographical regions. Wind speed and precipitation compound events – common during storms – were in the top three most common precipitation-related compound events in all regions (Ridder et al., *Nature Communications*, 2020).

Understanding where and at what time of year compound events of a given type occurred is useful. However, before simulating compound events under future climate conditions, it was necessary to determine whether existing state-of-the-art global models could accurately capture observed compound events. The research focused on two common compound events: co-occurring strong winds and heavy rainfall, and heatwaves and droughts. Using a new and innovative methodology, the first skill assessment of state-of-the-art climate models was completed and published in *Geophysical Research Letters* (Ridder et al., 2020).

TESTING THE SKILLS OF CLIMATE MODELS

It was shown that while some climate models could reproduce observed compound events well in the northern hemisphere, their accuracy diminished in the Southern Hemisphere, particularly over Australia. The research also showed that climate models with higher skills tend to project more significant increases in wet and windy events in the future as the climate changes.

In my latest publication in *Nature Climate and Atmospheric Science*, I show that by the end of the 21st century, heatwaves and drought, and strong wind and heavy precipitation co-occurrences are projected to increase significantly over large areas. This will result in a more than a doubling of co-occurrences of heatwaves and droughts – affecting 93–95% of the world's population. Furthermore, 64–76% of the world's population will see an increase in future wet and windy events.

The risks to human populations from compound events are increasing as the climate changes. It combines observations, reanalyses, and sophisticated and innovative statistical methods with climate model projections sourced from the most skillful models.

The methodology can be applied at regional scales and informed by new observations, new models and new understanding as they become available. As the risk of compound events increases, the work ensures they can be accurately included in risk assessments – including those performed by the insurance industry – thereby helping to reduce the vulnerability of human populations.

FORECASTING THE UNEXPECTED

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BIOGRAPHY

Lukas Schoppa is a Ph.D. researcher at the University of Potsdam and the German Research Centre for Geosciences (GFZ) in Potsdam, Germany. His research focuses on the dynamics of flood vulnerability in the commercial sector and employs methods such as Bayesian statistics, machine learning, and system dynamics. An environmental engineer by training, Lukas gained experience in (re-) insurance at the Munich Re flood risk group, which motivated him to investigate how the interactions between flooding and society shape risk.

TITLE OF THESIS

Dynamics in the Flood Vulnerability of Companies

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Water-related catastrophes are among the most frequent causes of loss events globally. During such events in Europe, the destruction of commercial assets amounts to up to 52% of the total loss. Still, current flood risk assessment suffers from a lack of comprehensive loss models for the sector and an inadequate representation of human-flood dynamics. An innovative approach deciphers the dynamics of company flood vulnerability.

The devastating flooding that struck Central and Western Europe in July 2021 again demonstrated the damage potential of extreme floods. More than 20 centimetres (7.9 inches) of rain fell in east Belgium over two days and 15 centimetres – a month's worth – in 24 hours in the west of Germany.

Streams burst their banks, cars and houses were washed away, streets smashed and as the rain continued, it triggered massive landslides so intense that part of the historic castle in Erfstadt was destroyed. At least 226 people died in Germany and Belgium. The damage has been estimated at up to €7 billion in losses.

Over the past 40 years, water-related perils have been among the most frequent causes of loss events globally, with damages totaling an estimated $1,092 billion (Munich Re, 2021). The destruction of commercial assets usually contributes considerably to overall flood devastation. In past such events in Europe, companies incurred up to 52% of the total event loss (Paprotny et al., 2020).

OVERLOOKING THE COMMERCIAL SECTOR

Flood loss models are indispensable in risk assessment and directly affect management decisions such as insurance pricing and the cost-benefit analysis of flood protection measures. Commonly, loss models quantify flood vulnerability by relating hydrological flood indicators such as inundation depth to the expected monetary loss.

In recent years, the improvement of flood loss models gained momentum due to the increasing availability of comprehensive loss datasets and advances in statistical modeling and machine learning. Yet, despite high shares of damages to companies, these model advancements rarely addressed the commercial sector.

Global change is increasingly influencing the drivers of flood risk. Climate change alters the frequency and intensity of floods, and urbanization accelerates the development of floodplains, increasing exposure. While changes in hazard and exposure are often considered in flood risk assessment, vulnerability dynamics, such as the capacity of society to adapt to flooding, are commonly not captured in state-of-the-art risk models. Nevertheless, dynamics in vulnerability can have a similarly significant effect on flood risk changes (Di Baldassarre et al., 2015; Kreibich et al., 2017).

In summary, current flood risk assessment suffers from a lack of comprehensive loss models for the commercial sector and an inadequate representation of human-flood dynamics. To bridge this gap, this research harvested new data streams and developed advanced models to capture the vulnerability dynamics of companies over long time scales.

TAILORED FLOOD LOSS MODELS FOR COMPANIES

Flood loss estimation for companies requires tailored-modeling solutions as companies are more heterogeneous than private households. For instance, companies operate in distinct economic sectors and differ in size, premises or equipment, which affects the processes that determine flood loss.

Therefore, the challenge was developing multivariable models that calculate the expected loss from hydrological indicators, company characteristics, precaution and flood experience instead of only inundation depth (Schoppa et al., 2020; 2021a). The models quantified predictive uncertainty via probabilistic loss estimates using approaches such as quantile regression forests, Bayesian networks, and Bayesian regression. In a validation experiment with a large company flood loss data set, the developed models outperformed the prediction accuracy of traditional models by up to 20% and reduced predictive uncertainty.

A SYSTEMS APPROACH TO FLOOD RISK ASSESSMENT

In conventional flood risk assessment, a limited set of hazard, exposure, and vulnerability scenarios are combined to make "snapshots" of flood risk at specific points in time. This approach neglects that flooding and humans are part of one interconnected system, with complex feedback mechanisms, which leads to fragmented and potentially misguided risk estimates.

The research used methods from the emerging field of socio-hydrology to assess how vulnerability and, thus, flood risk continuously evolves in time (Schoppa, L., Barendrecht M., Sieg, T., Sairam, N., & Kreibich, H. (2021b). "Augmenting a Socio-hydrological Flood Risk Model for Companies with Process-oriented Loss Estimation." In preparation). In detail, a Bayesian regression loss model was coupled to a socio-hydrological system dynamics model to trace how company flood risk changed at the river Elbe in Dresden, Germany, over the past 120 years.

The resulting process-oriented model was calibrated on empirical data and successfully captured the companies' flood adaptation, observed after a series of major flood events in the past 20 years. Further, the results revealed that companies behaved more risk-averse than private households.

This calibrated socio-hydrological model is being used to explore potential pathways of company flood risk in Dresden until the end of the 21st century. Further steps in the model development will address the application at larger spatial scales.

CONTRIBUTING TO MORE ROBUST INSURANCE PRICING

The socio-hydrological system dynamics model is a holistic approach to flood risk assessment as it generates multiple plausible flood risk trajectories. In contrast to traditional approaches, the method captures unexpected and often unintended co-evolutions of the human-flood system.

For instance, levee heightening often incentivizes the development of the hinterland, leading to even more considerable losses if a rare flood exceeds the protection level. In contrast, the negligence of societal adaption, which comprises actions such as relocation or the implementation of precautionary measures, overestimates the value at risk.

Through what-if analyses, the simulated risk trajectories can identify risk management strategies that reduce flood loss most effectively over decades. Consequently, the socio-hydrological flood risk model can contribute to more robust insurance pricing as it minimizes prediction biases. It also accounts for the characteristics of society, which actively shapes flood risk through land-use change, flood protection measures or private precaution.

Figure 1: *Representation of the coupled human-flood system as encoded in the socio-hydrological flood risk model. The model accounts for dynamics in hazard (blue), exposure (pink), and vulnerability variables (green) to continuously assess flood loss (orange)*

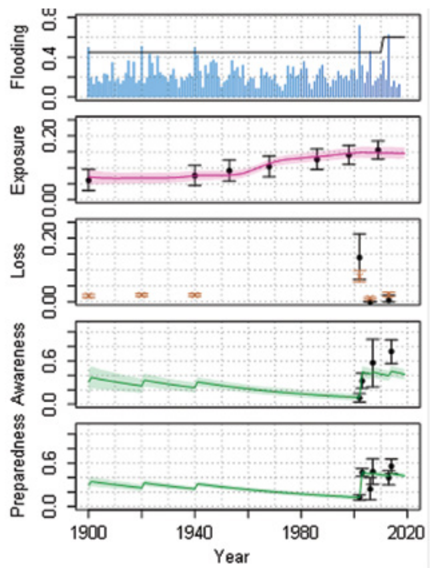
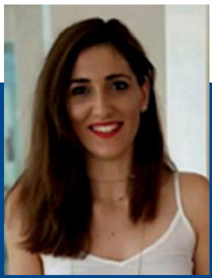


Figure 2: *Simulated (pink, orange, green) and observed (black, blue) co-evolution of the coupled human-flood system in Dresden, Germany, over the past 120 years. The socio-hydrological flood risk model is capable of capturing the governing flood risk dynamics.*

HELPING SMALLHOLDER FARMERS HELP THEMSELVES



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BIOGRAPHY

Eleftheria Vavadaki recently completed her Ph.D. at the Business School of Durham University, United Kingdom. She holds a Bachelors in Civil Engineering from the National Technical University of Athens (Greece) and continued her post-graduate studies in Water Resources Science and Technology at the same University. She has a Masters in Flood Risk Management organized by TU Dresden (Germany), IHE Delft (Netherlands), Technical University of Catalonia (Spain) and the University of Ljubljana (Slovenia). Her Ph.D. research was on financial instruments for disaster risk reduction in low- and middle-income countries, focusing on exploring factors that could affect the demand for hypothetical index-based flood insurance for crops in Nepal.

TITLE OF THESIS

Rethinking financial instruments: The case study of floods in Nepal

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Smallholder farmers in low- and middle-income countries have a perilous existence – one that climate change will make worse. Why then is the uptake of microinsurance so low, although it would significantly reduce their burden?

Buddha was born in Nepal, but otherwise, the heavens have not always smiled upon the small, landlocked nation. The country has always experienced more than its fair share of disasters: avalanches, drought, earthquakes, epidemics, fire, hailstorms, floods, landslides and thunderstorms.

Nepal's location in a seismically active part of the Himalayas, where many active faults meet, is an underlying physical cause. The situation is exacerbated by its rugged mountain topography, fragile geological nature and high-intensity rainfall during the monsoon. This means Nepal is extremely vulnerable to, for example, the rainfall-triggered landslides that wreaked havoc across the country in 2020.

Climate change means such disasters are likely to become more frequent and intense. It is no surprise, then, that Nepal ranked twelfth in the 2019 Global Climate Risk Index, an indicator of the country's exposure and vulnerability to extreme events.

With two-thirds of Nepal's population depending on agriculture for their livelihood, their hardscrabble existence is becoming ever more tenuous in the face of climate change. The number of farmers vulnerable to the impacts of natural hazards is growing significantly.

Nepal is not the only country where natural hazards wreak havoc. Floods are one of the most devastating natural hazards throughout South Asia and smallholder farmers bear the impact of flooding. Such events often shatter their livelihoods and then lock them into a vicious disaster-poverty cycle.

A critical challenge of our time is how to build the resilience of people and countries to the growing impacts of climate change? With this comes the question about finding suitable and sustainable solutions in the local context that work for the poorest in society.

This research tackled these questions by focusing on pro-poor financial instruments for reducing disaster risks. More specifically, it explored factors affecting farmers' demand for index-based flood insurance (IBFI) for agriculture in Nepal.

WHY AGRICULTURE NEEDS MICROINSURANCE

Microinsurance is designed for individuals on a low income and is usually offered for risks related to weather and agriculture. In Nepal, microinsurance for crops and livestock have been promoted since 2013 to increase the disaster resilience of farmers.

One of the innovative financial instruments for microinsurance is index-based insurance. This type of insurance is based on an index correlated with expected losses. Advantages of index-based insurance products include their low cost, fast payout and lack of complicated documentation for compensation once disaster strikes. One of the main disadvantages is basis risk, which is the mismatch between payments and losses.

Recent research in Nepal revealed that the demand for crops insurance of the current indemnity scheme remains low compared to livestock insurance. The Government of Nepal wants to explore if index-based microinsurance could be an option to improve the current scheme.

WORKING WITH LOCAL COMMUNITIES IN NEPAL

The research focused on the Lower Karnali River basin in western Nepal, an area subject to frequent floods. In 2019, I spent two months engaging with local communities and other stakeholders.

The study used a large-scale quantitative survey of local farmers, key informant interviews and focus group discussions to explore factors affecting farmers' demand for a potential IBFI for crops. An innovative game was developed and played with farmers across the Karnali River to encourage a discussion on the complex notion of index-based insurance.

FACTORS POSSIBLY AFFECTING FARMERS DECISION TO ADOPT INSURANCE

The research findings reveal that factors such as basis risk and education affect the willingness of farmers to pay for IBFI. For instance, farmers are unlikely to renew their contracts when they experience losses and do not receive compensation, due to basis risk (which is the mismatch between payments and occurred losses). A policy recommendation is to design index-based insurance products with minimum basis risk, while providing education on how insurance works. Both initiatives are critical to the success of a potential IBFI scheme.

Some further factors affecting the uptake of IBFI are related to applicability and implementation. For instance, previous experience with agricultural insurance is crucial when farmers dcide whether to engage with insurance. Negative past experiences relate to other types of agricultural insurance, such as complicated claiming procedures, are likely to affect the demand for potential IBFI.

Factors like the distance to the insurance provider can also create challenges when the farmers seek to renew their contracts. It has been suggested that rural organisations, such as cooperatives, could play a role to connect insurers and isolated farmers. Therefore, this type of approach should be further investigated to generate products that serve the needs of the farmers and sustainably protect livelihoods and societies.

PRACTICAL IMPLICATIONS

This research provided real-life evidence of factors that could hinder or enable the uptake of a potential IBFI scheme. Given that the research has been in partnership with an international non-governmental organisation (INGO), the findings could have an immediate practical implication in piloting IBFI in the study area.

In the long term, lessons learnt from this study could assist in up-scaling potential index-based insurance products related to other hazards in the study area. It could also serve as an example for other locations in the country and beyond.

Smallholder farmers living in low- and middle-income countries have one thing in common: their livelihood is subject to continuous natural shocks in combination with socioeconomic fragility – and climate change will make their existence even more perilous. IBFI schemes can provide them with a valuable safety net. The challenge is to design appropriate and sustainable insurance products that will encourage them to take them up.

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